

## INSTRUMENT POINTING CAPABILITIES: PAST, PRESENT AND FUTURE

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This paper surveys the instrument pointing capabilities of past, present and future space telescopes and interferometers. As an important aspect of this survey, we present a taxonomy for “apples-to-apples” comparisons of pointing performances. First, pointing errors are defined relative to either an inertial frame or a celestial target. Pointing error can then be further sub-divided into DC, that is, steady state, and AC components. We refer to the magnitude of the DC error relative to the inertial frame as absolute pointing accuracy, and we refer to the magnitude of the DC error relative to a celestial target as relative pointing accuracy. The magnitude of the AC error is referred to as pointing stability. While an AC/DC partition is not new, we leverage previous work by some of the authors to quantitatively clarify and compare varying definitions of jitter and time window averages. With this taxonomy and for sixteen past, present, and future missions, pointing accuracies and stabilities, both required and achieved, are presented. In addition, we describe the attitude control technologies used to and, for future missions, planned to achieve these pointing performances.

### I. INTRODUCTION

The purpose of this memorandum is to survey the instrument pointing capabilities of past, present and future space telescopes and interferometers. Pointing accuracy is quantified in terms of the pointing error, which can be defined relative to the inertial frame, or relative to a celestial target. Pointing error can be divided further into DC (steady-state) and AC components as proposed by Reference 1. In this memorandum we refer to the magnitude of the DC error relative to the inertial frame as the absolute pointing accuracy, and we refer to the magnitude of the DC error relative to a celestial target as the relative pointing accuracy. The magnitude of the AC error is referred to as the pointing stability. Pointing stability is defined for a particular frequency of AC error, or equivalently, the time period of the error. We assume no AC motion between the inertial frame and celestial target, hence we do not distinguish between relative and absolute pointing stability. This memorandum describes the pointing accuracy and pointing stability, both required and achieved, for past, present and future missions. We describe the attitude control technology required to achieve these capabilities.

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## II. OVERVIEW

For instruments performing precise imaging of celestial bodies, pointing stability is the driving requirement for high-quality imaging. The frequency of the pointing stability requirement is critical in determining the spacecraft design used to achieve the requirement. Figure 1 (bottom) shows a conceptual spectrum of disturbances than can affect the attitude of a spacecraft. Low frequency disturbances are generally external to the spacecraft, and come from sources such as solar pressure or atmospheric drag. High frequency disturbances come from internal sources, such as the reaction wheels, thrusters or the payload cooling system. Each disturbance source excites different structural modes of the spacecraft, as shown in Figure 1 (middle). At the far left of the spectrum (steady-state) are the rigid-body modes of the spacecraft, while on the right are flexible body dynamics, due to solar cells, for example. The frequency of the pointing stability requirement determines to what extent these vibrational modes need to be stabilized, which in turn determines the damping strategy used. Figure 1 (top) shows a conceptual spectrum of possible damping approaches. At low frequencies, the spacecraft Attitude Control System (ACS) can be used to correct pointing errors. An effective Attitude Control System requires both knowledge of the pointing error, and actuation to correct for the error. Attitude knowledge is usually provided with Star Tracker Assemblies (STAs) and gyros. Actuation for attitude control is usually achieved using Reaction Wheel Assemblies (RWAs). The performance of the RWAs is determined by their size and quantization level, both of which are parameters in the spacecraft design. Tight pointing stability requirements at low frequencies may cause a mission to require more accurate attitude knowledge than can be achieved using a conventional STA. In this case, there are two options. First, the mission can use an advanced STA system if one is available at reasonable cost. Second, the mission can use dedicated sensors on the payload to determine the pointing error relative to a celestial target; this is known as payload assist. For telescopic missions, payload assist is usually the preferred option, first because a high performance STA requires a large aperture, which the telescope payload provides at no extra cost, and second, because payload assist gives direct

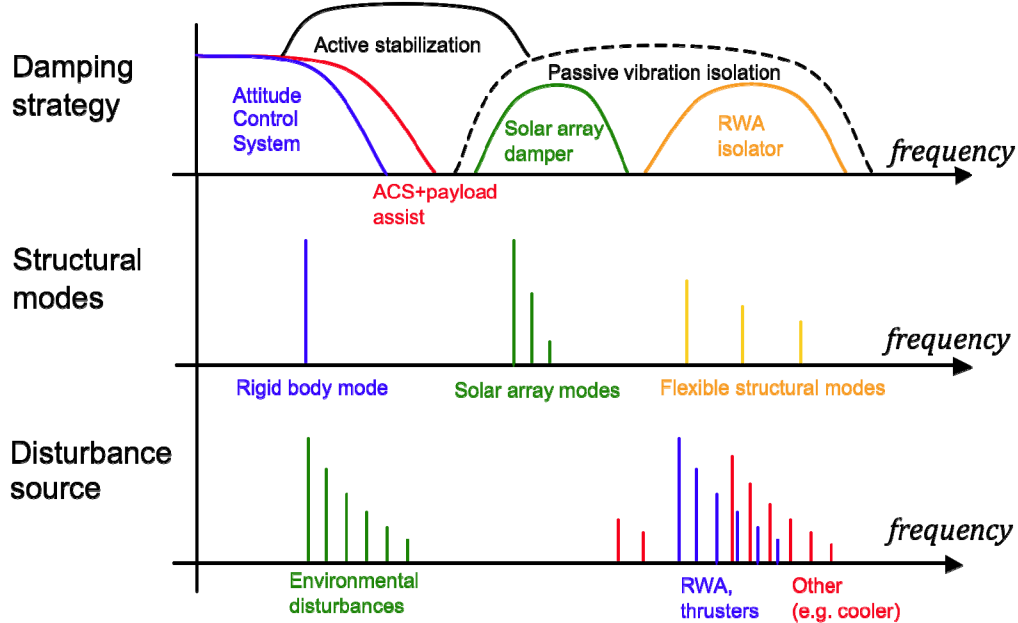


Figure 1: Conceptual frequency spectra of disturbance sources (bottom), spacecraft structural modes (middle) and strategies for damping these modes using either active or passive means (top).

knowledge of the telescope boresight error. By providing higher frequency attitude error information, payload assist increases the bandwidth of the ACS.

Above a few Hertz, the actuation capabilities of the ACS will not have sufficient bandwidth to correct attitude errors. Vibration in this frequency range is usually referred to as jitter. On many spacecraft this is not a problem since either the stability requirements at high frequencies are not stringent, or the disturbance sources do not excite the high-frequency modes of the spacecraft structure. This can occur when the spacecraft bus is relatively rigid and has high inertia. If this is not the case, high-frequency stability can be improved using either active stabilization or passive vibration isolation. One type of active stabilization uses Fast Steering Mirrors (FSMs) to correct errors in the light path without moving the spacecraft bus. Analogously to image stabilization on a camera, these mirrors can be actuated at much higher frequencies than the spacecraft itself since their inertia is much smaller. At even higher frequencies, the performance of FSMs and other active control techniques is limited by the ability to measure the high frequency pointing errors accurately. In this range, passive techniques, such as vibration isolators, must instead be used to ensure that disturbances do not affect the instrument. One example of a vibration isolator system is a RWA isolator, which prevents high-frequency RWA-induced disturbances from the RWA from reaching the instrument, but allows low frequency control actions to pass.

In Section III we describe the specific pointing requirements and designs for a number of past, present, and future astronomical space missions.

### III. MISSIONS

#### A. Infra-Red Astronomical Satellite

The Infra-Red Astronomical Satellite (IRAS) was launched on January 25, 1983, and operated for ten months in a sun-synchronous polar Earth orbit. IRAS was a joint project of NASA, the Netherlands Agency for Aerospace Programmes, and the Science and Engineering Research Council of the UK. IRAS performed all-sky surveys at infrared wavelengths, mapping 96% of the sky at wavelengths of  $12\mu\text{m}$ ,  $25\mu\text{m}$ ,  $60\mu\text{m}$  and  $100\mu\text{m}$ , at resolutions ranging from 30 arcseconds at  $12\mu\text{m}$  to 2 arcminutes at  $100\mu\text{m}$ . The instrument had a mirror diameter of 0.57m and a focal length of 5.5m.



Figure 2: The Infra-Red Astronomical Satellite

IRAS was required to achieve an absolute pointing accuracy of 30 arcseconds with a pointing stability of 10 arcseconds. For pointing, IRAS used two Fine Sun Sensors, and four rate integrating gyros. Two of these gyros were redundant, and controlled the attitude of the spacecraft about the sun-vector (the vector from the instrument to the sun).<sup>2</sup> Furthermore a V-slit two-axis star sensor was incorporated in the focal plane of the instrument to calibrate the attitude about the sun-vector, and to calculate the change in misalignment between the telescope and the attitude control sensors by measuring the transit times of preselected calibration stars over the slits. The two other gyros were added only to allow fine control of the instrument during eclipses, however this capability was not used in flight due to the reduced control accuracy. IRAS used three orthogonal reaction wheels, with three orthogonal magnetic coils used to transfer excess angular momentum to the Earth.<sup>2</sup>

#### B. Hipparcos

The High Precision Parallax Collecting Satellite (Hipparcos) was an ESA mission launched on August 8, 1989, in order to measure stellar parallax and the proper motion of stars. The mission lasted 3.5 years and took place in an Earth elliptical orbit. Initial plans were for a geostationary orbit, however the apogee boost motor failed resulting in an elliptical orbit; all scientific goals were accomplished nonetheless. The main instrument had a mirror diameter of 0.28m and a focal length of 1.4m.<sup>3</sup>

An extremely smooth satellite motion was required because of the measurement principle; phase extraction of light from stars was sensitive to any jitter during the sequence. Furthermore astrometric accuracy was improved by interlacing bright and well-measured stars along a great circle; this approach also relied on a very smooth and predictable motion. On the other hand, the absolute pointing requirements were very loose at  $\pm 600$  arcseconds. As a result, Hipparcos used specially designed 0.02N cold gas thrusters for attitude control with a  $\pm 600$  arcseconds deadband.

Observations were carried out in the 400 seconds or so between firings, meaning that effectively no attitude control took place during observations; this led to extremely smooth spacecraft motion during observations.<sup>4</sup>



Figure 3: The Hipparcos Spacecraft

### C. Hubble Space Telescope

The Hubble Space Telescope, launched on April 24, 1990, was the first of NASA's Great Observatories. When launched, Hubble carried five scientific instruments operating in the optical and ultra-violet wavelengths. Hubble operates in low Earth orbit, and current plans call for operations to continue until at least 2013. The telescope's main mirror has a diameter of 2.4m and a focal length of 57.6m.<sup>5</sup>



Figure 4: The Hubble Space Telescope

To achieve high quality imaging of some of the universe's most distant objects, Hubble is required to achieve a radial pointing stability of 0.007 arcseconds RMS over periods between 60 seconds and 24 hours.<sup>6</sup> Attitude control is provided by four RWAs that have spin axes skewed relative to the vehicle frame in order to provide redundancy. The high-frequency disturbances from the RWAs would, by themselves, excite the secondary mirror modes. To attenuate this coupling, each RWA is mounted on passive isolators.<sup>6</sup> Angular rates are provided by a skewed set of six integrating Rate Gyro Assemblies (RGAs). To improve low-frequency performance, Hubble uses a Fine Guidance Sensor (FGS) both for astrometric observations and to determine the high-frequency pointing error relative to known star positions<sup>5</sup>. Hubble therefore uses attitude control, passive isolation and payload assist to satisfy its extremely stringent pointing requirements.

During flight, two unique sources of pointing jitter were discovered. The first was due to unexpected disturbances originating in the solar arrays.<sup>6</sup> The second disturbance consisted of vibrations from the cryo-cooler, which was installed in 2002 to cool the Near Infrared Camera and Multi-Object Spectrometer Instrument (NICMOS).<sup>7</sup> To satisfy pointing requirements despite these disturbances, the attitude control algorithms were redesigned several times, as described in detail in Reference 6. In addition the solar arrays were replaced in 2002 with more rigid arrays in order to allow Hubble to survive re-boost to a higher orbit. These solar arrays included a set of dampers that reduce the coupling between the solar array modes and the Hubble spacecraft bus, and further improved pointing stability.<sup>8</sup> Hubble achieves an absolute pointing accuracy of between 1 and 2 arcseconds and a pointing stability of 0.002 arcseconds RMS, radial. This is an improvement of two orders of magnitude over precision pointing missions designed in the same era, which is possible only due to the inclusion of payload assist (FGS) and isolator technology.

#### **D. Compton Gamma-Ray Observatory**

The Compton Gamma-Ray Observatory (CGRO) was launched on April 5, 1991. CGRO was part of NASA's Great Observatories Program, which also includes the Hubble Space Telescope, Spitzer and the Chandra X-Ray Observatory. It was operated until June 4, 2000, in low Earth orbit in order to avoid the Van Allen radiation belt. CGRO measured the electromagnetic spectrum from 20keV to 30GeV, using four instruments known as the Burst and Transient Source Experiment (BATSE), the Oriented Scintillation Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL), and the Energetic Gamma Ray Experiment Telescope (EGRET). Each of the four instruments had an improvement in sensitivity of a factor of ten over previous missions.<sup>9</sup>

CGRO had an absolute pointing accuracy requirement of 1800 arcseconds, and a stability requirement of 60 arcseconds, radial. The spacecraft was three-axis stabilized, with control provided by four reaction wheel assemblies. Momentum dumping was performed by magnetic torquers. Attitude sensing was provided by three fixed-head star trackers, four inertial reference gyros, and course and fine sun sensors.<sup>10</sup>

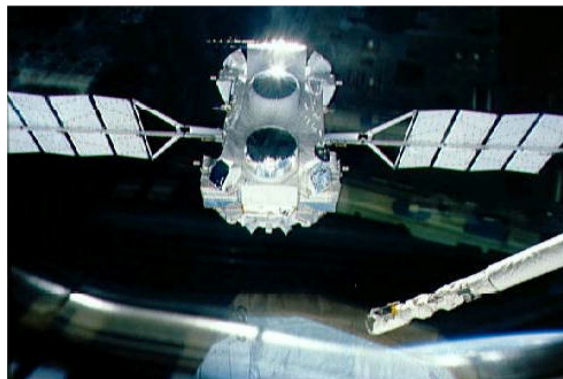


Figure 5: CGRO After Deployment from the Shuttle Orbiter

#### **E. Infrared Space Observatory**

The Infrared Space Observatory (ISO) was operated by the European Space Agency (ESA) and was launched by Ariane 44P on November 17th 1995. ISO operated from 1995 to 1998, with a Post-Operational Phase until 2006. ISO was designed to provide astronomers with a capability for detailed exploration of the universe at infrared wavelengths. At a wavelength of 12 $\mu$ m, ISO was one thousand times more sensitive and had one hundred times better angular resolution than the earlier IRAS mission.<sup>11</sup> The ISO telescope had an aperture of 0.60m and a focal length of 9m.



ISO was placed in a highly elliptical Earth orbit. The scientific payload of ISO consisted of an imaging photopolarimeter, a camera, a long wavelength spectrometer and a short wavelength spectrometer. These instruments enabled photometry in broad and narrow spectral bands across the entire range of wavelengths from  $2.5\mu\text{m}$  to  $240\mu\text{m}$ .<sup>12</sup>

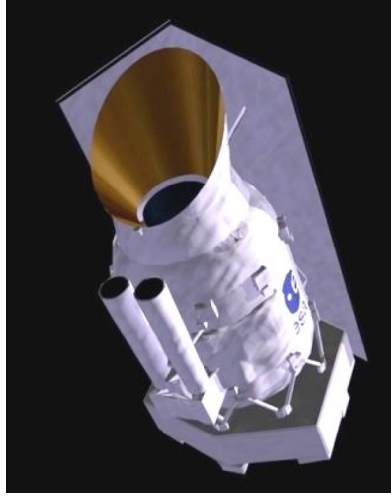


Figure 6: The Infrared Space Observatory (Credit: ESA)

The ISO spacecraft was required to achieve 11.7 arcseconds radial absolute accuracy at 2-sigma, and 2.7 arcseconds half-cone stability at 2-sigma over a time period of 30s. The drift had to be less than 2.8 arcseconds (half-cone, 2 sigma) per hour. ISO used sun and earth sensors, star trackers, a quadrant star sensor on the telescope axis and gyros to perform attitude sensing. Actuation was provided by reaction wheels and a hydrazine reaction control system. After detailed ground analysis and a variety of tune-ups, an in-flight absolute accuracy of 1 arcsecond was achieved, and the stability was improved to around 0.5 arcseconds. A drift of 0.1 arcseconds per hour was achieved in flight.<sup>12</sup>

#### **F. Chandra**

The Chandra X-ray Observatory is the X-ray component of NASA's Great Observatories program. Chandra was launched on July 23, 1999, from the Space Shuttle Columbia and operated in a highly elliptical Earth orbit. The pointing requirements of Chandra are less stringent than other instruments (e.g. Hubble) because the X-ray detectors are essentially single-photon counters; hence an accurate post-facto history of the spacecraft pointing direction is sufficient to reconstruct the image accurately.<sup>13</sup> Chandra has a mirror diameter of 1.2m and a focal length of 10m.



Figure 7: Chandra X-ray Observatory

The absolute 99% pointing accuracy requirement for Chandra is 30 arcseconds, with 0.25 arcseconds RMS half-cone angle per axis pointing stability in 95% of all 10 second periods. Chandra uses two Inertial Reference Units (IRUs, each containing two 2-axis gyroscopes), six reaction wheels, and a reaction thruster system. In order to isolate the instrument from high-frequency disturbances from the reaction wheels, Chandra has a hexapod isolator at each of its six reaction wheels.<sup>14</sup> Each element of the hexapod comprises compound titanium slotted springs, with dampers in parallel with the softer of the springs.<sup>15</sup> For precision pointing sensors, Chandra uses an aspect camera and a fiducial system. While the pointing requirements could be satisfied using an advanced star tracker system, instead Chandra uses a conventional star tracker combined with the aspect camera to reduce cost. The aspect camera tracks a number of guide stars (normally five) and fiducial lights (normally three). Several guide stars are used so that averaging across stars can be used to mitigate errors in star centroid determination. The fiducial lights consist of a set of light emitting diodes that register the focal plane of the detector laterally with respect to the boresight of the aspect camera.<sup>13</sup> The fiducial light positions map the x-ray detector coordinate system and x-ray photons onto the celestial sphere. Image reconstruction uses the angular differences between successive measurements of the stars and fiducial lights to register x-ray photons in the same location.<sup>13</sup> Since the fiducial lights and aspect camera are used for calibration updates, rather than being a part of the attitude stabilization loop, they are not considered as a payload assist system. The absolute accuracy achieved in flight was 3 arcseconds and the pointing stability was 0.04 arcseconds RMS per axis (10 seconds). During the mission, however, gyro 2 suffered increased bias drift rates and noise rates that decreased the pointing stability to 0.10 arcseconds for 7 days.

### **G. X-Ray Multi-Mirror Mission**

The X-Ray Multi-Mirror Mission (XMM-Newton) was launched on December 10th, 1999, into an elliptical Earth orbit. XMM-Newton is operated by the European Space Agency, and is expected to continue until at least 2010. XMM-Newton carries three X-ray telescopes, each containing 28 Wolter-type concentric mirrors with diameters ranging from 0.3m to 0.7m and a focal length of 7.5m. The instruments onboard consist of three European Photon Imaging Cameras (EPIC), two reflection-grating spectrometers and a Ritchey-Chretien optical/UV instrument. In addition the spacecraft carries a particle detector to measure radiation that can perturb the CCD detectors of the main science instruments.



Figure 8: The XMM-Newton Spacecraft (Credit: ESA)



XMM-Newton was required to achieve 60 arcseconds of radial absolute pointing accuracy and 0.25 arcseconds of pointing stability. The spacecraft uses four 0.2Nm reaction wheels for fine attitude control, with hydrazine thrusters for coarse control and momentum management. Two star trackers and a sun sensor are used for attitude sensing.<sup>16</sup>

### **H. Galaxy Evolution Explorer**

The Galaxy Evolution explorer (GALEX) was launched on April 28, 2003, into a circular low Earth orbit. GALEX is operated by NASA, and makes observations at ultraviolet wavelengths in order to study the history of star formation in the Universe. To do so, GALEX determines the distance of thousands of galaxies and the speed of star formation in each galaxy. The spacecraft carries a telescope with a primary mirror diameter of 0.5m and a secondary mirror diameter of 0.22m. Instruments onboard consist of two micro-channel plate detectors sensitive to ultraviolet light from 175nm to 280nm. These instruments produce circular images of the sky with 5 arcsecond resolution in two UV light bands, and spectra with 10 to 20 angstrom resolution of all objects in the field of view.

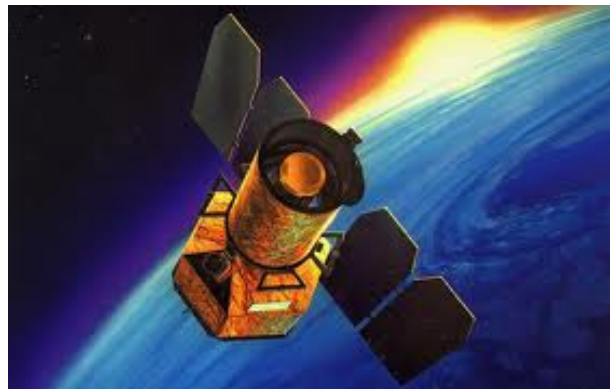


Figure 9: The GALEX Spacecraft

The attitude control system uses two gyroscope systems; a Litton Space IRU (SIRU) hemispherical resonating gyroscope and an RGA20 ring laser gyroscope. For pointing control, the spacecraft uses four Ithaco reaction wheel assemblies, two magnetic torque bars, and one magnetic torque coil. Attitude information is obtained using eight coarse sun sensors, one three-axis magnetometer, and a Ball CT-633 star tracker. When the Sun is visible, the attitude control system provides coarse sun pointing to charge the solar cells. The spacecraft then performs a 6 minute scan before slewing to a science target; during science pointing, GALEX achieves a radial pointing accuracy of 300 arcseconds with 0.3 arcseconds RSS radial stability over 10 second windows, and a spiral dither of a few arcseconds/s during deep pointings.<sup>17</sup>

### **I. Spitzer**

The Spitzer space telescope, previously known as the Space Infrared Telescope Facility, was launched on August 23, 2003, into a heliocentric orbit. The last of NASA's Great Observatories, Spitzer is an infrared spectrum observatory with a mirror diameter of 0.85m and a focal length of 10.2m. Spitzer was the first mission to execute astronomical observations from an Earth-trailing heliocentric orbit, and supports three instruments; the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer for Spitzer (MIPS). Together these instruments provide imaging, photometry and spectroscopy in the 3-180 micron wavelength range. Spitzer is cryogenically cooled to 5.5K, which, combined with improved detector array technology, enables a factor of 100- 10,000 gain in sensitivity over previous infrared missions. Spitzer is expected to continue operation until April of 2009.<sup>18</sup>

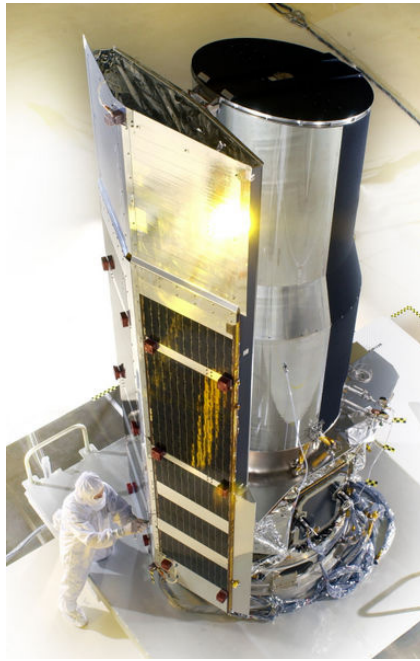


Figure 10: The Spitzer Space Telescope

Spitzer is required to achieve a radial absolute pointing accuracy of 5 arcseconds or better (1-sigma), and 0.6 arcseconds (1-sigma) radial stability over 500 seconds. Pointing control is carried out using four 0.04N reaction wheel assemblies, which are periodically desaturated with nitrogen cold-gas thrusters. The reaction wheels are mounted in a pyramid orientation about the telescope boresight axis. Attitude determination is performed using star trackers, and inertial reference unit, wide-angle sun sensors, and Pointing Calibration Reference Sensors (PCRS). The star trackers provide star position measurements at 2Hz with an absolute accuracy (1-sigma) of 1.5 arcseconds per star with a noise equivalent angle of 0.75 arcseconds per axis per star (1 sigma). The inertial reference unit employs two dual-axis, spinning-mass gyros that measure angular rate relative to inertial space. The PCRS is located on the telescope focal plane, and is used to calibrate for changes in telescope-to-spacecraft alignment that may drift due to thermo-mechanical effects.<sup>19</sup> Since the PCRS is used for periodic calibration updates, rather than constant attitude stabilization, it is not considered payload assist. In achieving high-performance pointing stability, Spitzer benefits from a spacecraft bus that has high inertia and is rigid, due to the position of the solar panels. In addition, the reaction wheels are small. This means that high-performance stability can be achieved without the need for vibration isolators.

Since the lifetime of the Spitzer mission is inherently limited by the amount of cryogen carried on board, it is essential that accurate pointing is achieved quickly. In addition, heat-absorbing sensors had to be minimized in size or avoided altogether. Several advances in attitude estimation were required to overcome these challenges. The limiting factor in achieving accurate pointing is attitude estimation performance; existing estimators, based on Kalman Filtering, have unacceptably slow settling times. As a result, a completely new estimation capability, known as Fast Observers, was developed. These observers have guaranteed fast settling times, while retaining almost all of the covariance-optimality of the Kalman Filter. This, along with a number of other advances in attitude estimation, enables Spitzer to achieve an in-flight absolute pointing accuracy of 0.45 arcsecond (1-sigma, radial) and a 0.02 arcsecond stability (1-sigma, radial) over 500 seconds.<sup>19</sup>

## J. AKARI

The AKARI mission was launched by JAXA on February 21, 2006. Its primary mission is to survey the entire sky in near, mid and far infrared with its 0.69m aperture telescope, which has a focal length of 4.2m. The spacecraft is cooled by liquid helium, which has now been depleted; the spacecraft is currently in its post-helium phase where near-infrared sensors are still operational. AKARI is in a Sun-synchronous polar earth orbit. AKARI operates in two modes; pointing mode and survey mode. In pointing mode, the telescope points at an area of the sky for up to ten minutes. In survey mode, the telescope scans the sky with a constant speed of 3.6 arcmin/sec.

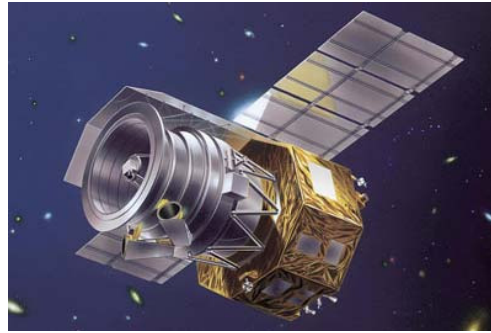


Figure 11. The AKARI Spacecraft (Credit: JAXA)

AKARI's attitude control system consists of gyros, a two-dimensional fine sun sensor, and a pair of star sensors. The sun sensors were used to monitor the position of the Sun in two dimensions perpendicular to the Sun-satellite direction, and to correct any long-term drift of the IRU. The star sensors are used to observe the attitude along the third axis, and the alignment change between the gyros and sun sensor, and the telescope. Reaction control wheels and magnetic torque rods are used for attitude control. In pointing mode, AKARI achieves an absolute radial pointing accuracy of 30 arcseconds, with a 1 arcsecond radial stability over 60 seconds. In survey mode, AKARI achieves an in-scan stability of less than 0.1 per cent error, and a cross-scan stability of approximately  $3 \times 10^{-5}$  deg/sec (3-sigma).<sup>20</sup>

## K. COROT

The COROT (CONvection ROTation and planetary Transits) mission is led by CNES in conjunction with ESA and other partners, and has two objectives: the first is to search for extrasolar planets with short orbital periods, particularly those of large terrestrial size, and the second is to perform asteroseismology by measuring solar-like oscillations in stars. COROT was launched on December 27, 2006, and it detected its first extrasolar planet in May of 2007. COROT has a 0.27m afocal telescope with an array of spectroscopic detectors, and is in a polar Earth orbit.<sup>21</sup>

The spacecraft is required to achieve a pointing stability of 0.5 arcseconds per axis (1-sigma). The attitude control system uses the output of the instruments (payload assist) to determine the position error of two asteroseismology targets, and hence determine the fine angle error data.<sup>21</sup> Attitude control was provided by reaction wheels and a magnetic torque bar. Since high-frequency structural modes were not a concern with COROT, the stability requirements could be achieved without the need for vibration isolation. In flight, COROT has achieved a stability of 0.25 arcseconds per axis.<sup>22</sup>

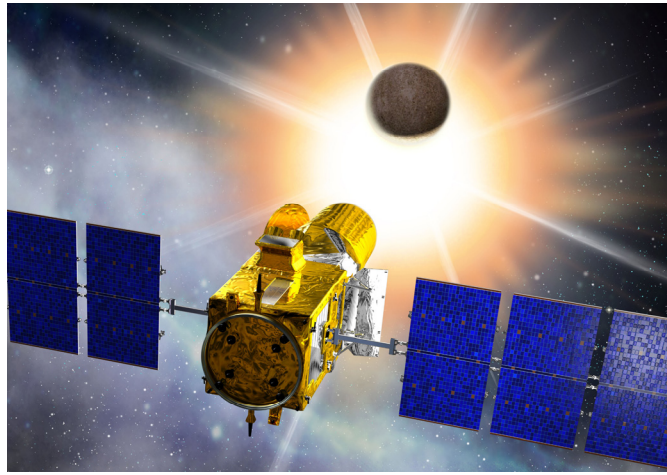


Figure 12: The COROT Spacecraft

### L. Kepler

Kepler is a space-based photometer for detecting planets outside of the Solar System, known as exoplanets, launched in March of 2009 into an Earth-trailing heliocentric orbit. A space-based photometer can detect the periodic transits of earth-class planets for a variety of stars, and from this data we can determine the orbital semi-major axis, size and characteristic temperature of each planet. In addition the frequency of planet formation for systems of single and multiple stars can be determined.<sup>23</sup> The Kepler photometer has an aperture of 0.95m and a mirror diameter of 1.4m. An array of 42 charge coupled devices (CCDs) mounted on the focal surface of the telescope measures variations in stellar brightness.<sup>24</sup>

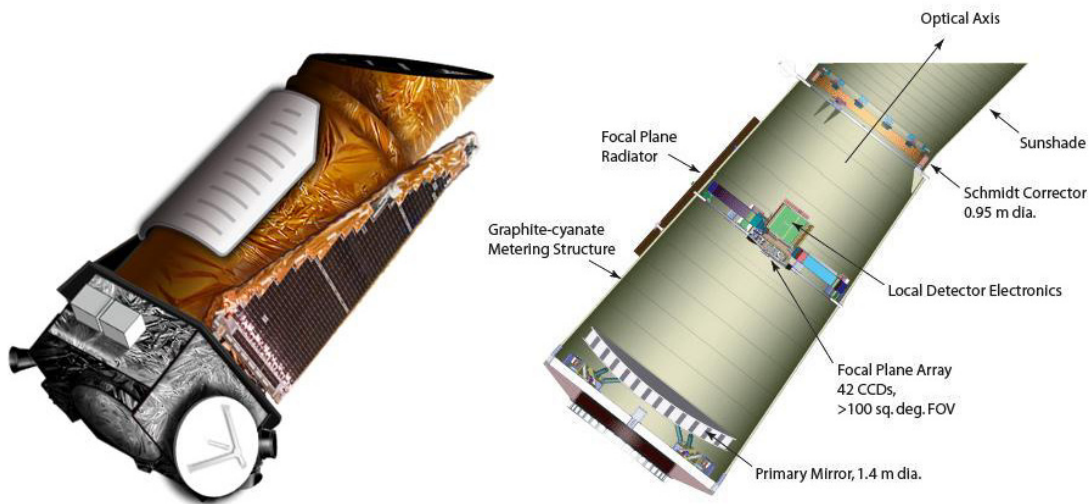


Figure 13: The Kepler Spacecraft

Attitude stability is essential in achieving the photometric precision necessary for this mission. Image motion affects the photometric precision adversely because of both the extended tails of the light point-spread function and variations in inter- and intra-pixel responsivity. As a result, Kepler must achieve a stability of 0.010 arcseconds (1-sigma) per axis over a time period of 900 seconds.<sup>25</sup> This will be achieved using gyros, reaction control wheels and an FGS system. The FGS consists of four CCDs mounted to the scientific focal plane at the four corners, to prevent



long-term drifts. Ten coarse sun sensors and two star trackers will be used for initial target acquisition, while twelve hydrazine thrusters will be used to dump momentum. Although high performance pointing stability is required, it is over a long time period. This means that vibration isolators are not required to meet the stability requirements.

### **M. Herschel and Planck**

Herschel is the first space observatory to make observations across the full far-infrared and sub-millimeter wavelength range. By making observations at wavelengths from 60 to 670 microns, Herschel will bridge the gap between what can be observed using ground and airborne facilities, and prior space missions such as ISO.<sup>26</sup> Planck will systematically image the whole sky between 30 and 900GHz to determine the temperature fluctuations of cosmic background radiation. Both Planck and Herschel are operated by the European Space Agency (ESA) and were launched on a single Ariane 5 rocket on May 15th, 2009. The spacecraft orbits around the Sun-Earth L2 point.

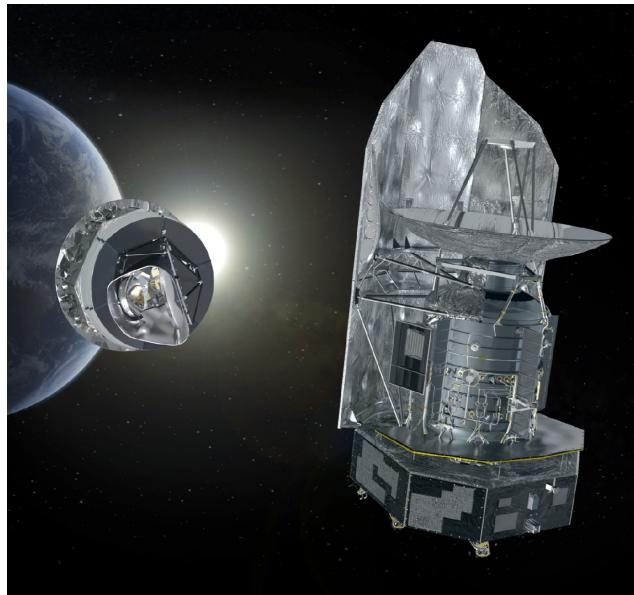


Figure 14. Planck Spacecraft (left) and the Herschel Space Observatory (right) (Credit: ESA)

Herschel has a mirror diameter of 3.5m and a focal length of 27m. The pointing requirements for Herschel are 3.7 arcsecond per axis absolute accuracy, and 0.3 arcsecond per axis stability over 60 seconds. In normal operation, the spacecraft attitude is controlled by means of the reaction wheel system, which consists of four 8.6kg wheels in a skewed configuration. The attitude is determined using both star trackers and gyroscopes. It is anticipated that Herschel will achieve 2.5 arcseconds per axis absolute accuracy and 0.24 arcseconds per axis stability.<sup>27</sup>

Planck performs surveys of the entire sky, and therefore has very loose pointing requirements. The spacecraft is spin-stabilized at 1 rpm, achieving an absolute pointing accuracy of 480 arcseconds and a pointing stability of 18 arcseconds. Planck uses a star tracker to determine its attitude, as well as a coarse rate sensor, a sun acquisition sensor, and an attitude anomaly detector.

### **N. Wide-field Infrared Survey Explorer**

The Wide-field Infrared Survey Explorer is a NASA-funded project to perform an all-sky survey in the 3 to 25 micron wavelength range. This survey is more than 500 times more sensitive than the earlier IRAS or AKARI missions.<sup>28</sup> The spacecraft operated in a sun-synchronous polar

Earth orbit for its seven month mission, taking 1.5 million 11- second exposure images, each covering a 47 arcminute field of view. WISE has a mirror diameter of 0.4m and launched on 14th December 2009. WISE's primary mission ended in October of 2010.

During science pointing, the telescope was required to scan a semicircle about the sky at a constant orbital rate. While this occurs, a single-axis motorized scan mirror freezes each image for 9 seconds of an 11-second scan cycle.<sup>29</sup> The pointing requirements for WISE are 75 arcseconds (1-sigma) per axis absolute accuracy, with 1-sigma stability of 0.6, 0.5, and 0.9 arcseconds in roll, pitch, and yaw, respectively, over 8.8 seconds. The spacecraft was three-axis stabilized with one star tracker, an inertial measurement unit with three gyros and accelerometers, a three-axis magnetometer, fourteen coarse sun sensors, three off-axis orthogonal reaction wheels, and torque rods.<sup>29</sup>



Figure 15. The WISE Spacecraft

### **O. James Webb Space Telescope**

The James Webb Space Telescope (JWST) is a collaboration between NASA, ESA and the Canadian Space Agency, due to launch on an Ariane 5 rocket in June of 2013. Formerly known as the Next Generation Space Telescope (NGST), JWST is an infrared spectrum observatory spanning the range from 0.6 to 28 microns. JWST's mission has four components; to search for light from the first stars and galaxies that formed after the Big Bang; to study the formation and evolution of galaxies; to understand the formation of stars and planetary systems; and to study the origins of life.<sup>30</sup> Operating at the Sun-Earth L2 point, the spacecraft will be radiatively cooled to 40K, and will use a deployable sunshield to block infrared radiation from the Sun, Moon and Earth. JWST has a 6.5m segmented mirror with a focal length of 131.4m; this mirror has over seven times the collecting area of the Hubble space telescope and will unfold after the telescope separates from the launch vehicle.

To achieve the requirements on image quality delivered by the Near-Infrared Camera, the following pointing requirements are imposed on JWST. First, the line-of-sight stability must be better than 0.005 arcseconds RMS. Second, the change in mean pointing over a time scale of a few seconds should be less than 0.0035 arcseconds. Third, the roll stability has to remain below 0.0035 arcseconds.<sup>31</sup> To satisfy all of these requirements, JWST will use an FGS, a Fine Steering Mirror (FSM) and a passive vibration isolator. Tuned magnetic dampers have also been added to the design to mitigate vibrations at low RWA speeds.<sup>32</sup> The Fine Guidance Sensor will be used



for fine pointing control during all science observations and as a science imager to acquire narrow band NIR images of a variety of astrophysical targets.<sup>33</sup> The FGS uses a guide star to determine the attitude of the telescope about one axis. The FSM corrects for small motions of the telescope by steering in the direction opposite to the disturbance. The passive isolator is used to isolate vibrations in the main spacecraft from the mirror. Vibration is particularly problematic on JWST because of its high flexibility and low operating temperature. The high flexibility is a result of the large aperture combined with size and weight limitations of launch vehicles, while the low temperature causes the damping of the structure to be less than at room temperature.<sup>15</sup> The isolator chosen for JWST consists of four passively damped beams connecting the corners of the spacecraft to a thermal isolation tower positioning the telescope.<sup>15</sup>

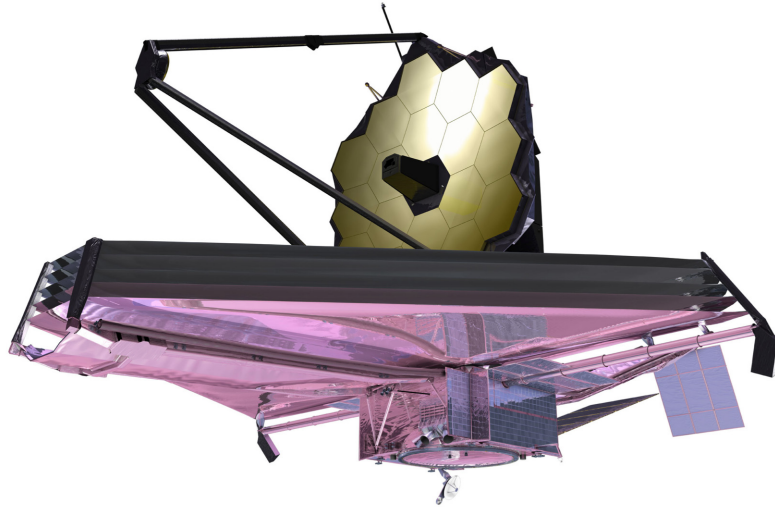


Figure 16. The James Webb Space Telescope

### **P. Space Interferometry Mission**

The Space Interferometry Mission (SIM) was a NASA mission planned to launch in 2015 or later. While SIM was cancelled in late 2011, we include it for completeness. SIM planned to use space-based interferometry in the visible spectrum to detect exoplanets and perform galactic mapping. Interferometry on SIM would use two 0.3 m collectors separated by 9 m in order to achieve resolutions commensurate with a much larger monolithic mirror. SIM would have operated in an Earth-trailing heliocentric orbit. The starlight from both collectors would be combined in a central unit known as the combiner. Light would arrive at each collector at a slightly different time, and by determining the difference in optical path length between the light received in each collector unit, interferometry would accurately determine the angle between the baseline of the interferometer and the star. This would be achieved by delaying the light wave from one of the collectors using an optical delay line. The difference in optical path length would then be determined by tracking a central fringe of light, which appears when the path length difference due to the optical delay is identical to that due to the external difference in arrival times at the two collectors.<sup>34</sup>

SIM was planned to operate in either scan mode or fine pointing mode. In scan mode, SIM would be required to achieve an absolute pointing accuracy of 2 arcseconds per axis and a pointing stability of 0.2 arcseconds per axis over a period of 20 minutes. In fine pointing mode, SIM would be required to achieve a relative pointing accuracy of 0.030 arcseconds per axis and point-

ing stability of 0.014 arcseconds per axis. The absolute pointing requirements are driven by the need to determine that a selected guide star falls within the field of view of the coarse acquisition camera of the guide interferometer. The spacecraft pointing stability requirements are driven by the need to maintain a high level of optical path-length stability over the 0.01s integration time of the fringe acquisition process. Good path-length stability leads to high signal-to-noise ratios for optical fringe detection.<sup>34</sup>

SIM planned to use inertial reference units and star trackers to determine its attitude. Three reaction wheel assemblies would be used to control the spacecraft base-body (with a fourth acting as a backup). Thrusters would be used periodically for momentum dumping.<sup>34</sup> Each of the RWAs would have vibration isolators similar to those used for Chandra. For angular control of the incoming starlight, SIM planned to use two steerable mirror systems for active stabilization. The first is known as the Siderostat (SID), which operates over a large ( $15^\circ$ ) field of regard at low bandwidths. The second is the FSM, which would be used to steer the line of sight for the guide compressors. The FSMs are piezoelectrically operated and would have much smaller range than the SID, but could reject high-frequency disturbances due to thermal and mechanical effects.<sup>34</sup> In order to satisfy its pointing requirements, therefore, SIM planned to use attitude control, payload assist, active stabilization and vibration isolation.

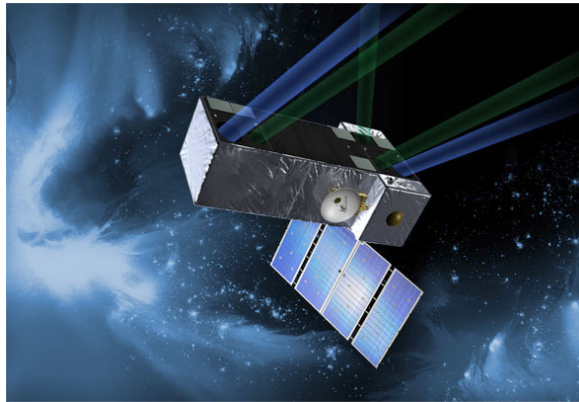


Figure 17. The SIM Spacecraft

#### IV. CONCLUSION

This paper has surveyed the pointing requirements of past, present, and future space observatories. We have provided details of the attitude control technology used to achieve the required pointing accuracy and stability, and have, where applicable, given results for the pointing performance achieved in flight. For missions performing precise imaging, pointing stability is the driving requirement. In order to achieve the best possible pointing stability at all frequency ranges, future missions plan to use all existing vibration damping techniques, including attitude control, payload assist, active stabilization and vibration isolation.

#### V. ACKNOWLEDGMENT

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